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THE EFFECTS OF STEAMING ON SHIP DOWNTIME AND FUEL CONSUMPTION.(U)

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<sup>20</sup> effects of various factors besides steaming are also measured, including ship's fleet (Atlantic or Pacific), ship's class, and time since overhaul.

Steaming's effects on diesel, JP5, and other fuel are estimated for each of 13 ship classes and also for the typical destroyer.

<sup>7</sup>Contributor: Claire Hughes

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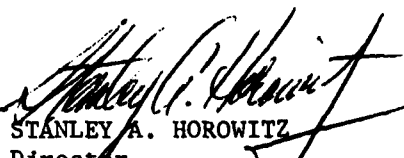
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# **THE EFFECTS OF STEAMING ON SHIP DOWNTIME AND FUEL CONSUMPTION**

Lawrence Goldberg



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**CENTER FOR NAVAL ANALYSES**

2000 North Beauregard Street, Alexandria, Virginia 22311

## INTRODUCTION

### Fuel Prices and Steaming

After five years of nearly stable prices, fuel prices more than doubled in FY 1974. Since then they have continued to increase but much more slowly. Fiscal constraints induced by fuel price increases have caused the Navy to restrict steaming.<sup>1</sup>

Evidence of steaming declines is given in table 1, which reports average hours of (1) steaming underway, (2) steaming not underway and (3) not steaming for 91 destroyers, cruisers and frigates, FY 1966-1975.

Hours of steaming underway is a measure of operating tempo: the crew is relatively active operating the ship and undertaking training exercises. Except where it might be confusing, we will follow the Navy's practice and refer to steaming underway as simply "steaming."

Hours steaming not underway are periods of relative inactivity. Although energy needs are met from its own boilers, ship systems are operated at a slower pace and the crew undertakes fewer training exercises. Hours not steaming are periods of minimum activity: ship's boilers are turned off and energy is provided from shore through an electrical hookup.

Relative to FY 1973, steaming underway declined by 92 hours per month (33 percent) over FY 1974 and FY 1975. Changes in steaming not underway were relatively small in both years: it declined by 19 hours in FY 1974 but increased by 10 hours in FY 1975. Thus, a one hour decline in steaming underway resulted in roughly a one hour increase in hours not steaming.

A trend analysis of the years prior to FY 1974 yields the finding that steaming underway per month was declining by two hours per year. Forecasts of steaming underway (given in parentheses in table 1) are 249 for FY 1974 and 247 for FY 1975. Compared with trends, steaming underway declined an average of 60 hours per month in FY 1974 and FY 1975. The additional decline of about 25 percent was probably caused by fuel price increases.

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<sup>1</sup>"FY 1978 Major Issue: Impact of Oil Prices on Naval Operations," unpublished paper, Op-96.

TABLE 1

AVERAGE MONTHLY HOURS STEAMING UNDERWAY, STEAMING NOT UNDERWAY, AND NOT STEAMING FOR 91 DESTROYERS, CRUISERS AND FRIGATES, BY FISCAL YEAR 1966-75

	Fiscal Year										
	66	67	68	69	70	71	72	73	74 <sup>a</sup>	75 <sup>a</sup>	
Steaming	264	283	285	258	229	252	241	280	187	189	
Underway									(249)	(247)	
Not underway	215	199	192	188	185	166	134	138	119	129	
Not steaming <sup>b</sup>	251	248	253	284	316	312	355	312	425	411	

Source: Steaming and Fuel Data Master File.

aForecasts of steaming underway based upon a trend analysis of fiscal years 1966-73, are given in parentheses. The actual levels of steaming underway in FY 1974, 187, and in FY 1975 189 are about 25 percent less than "predicted" by the trend analysis.

bIt is assumed there are 730 hours in a month. Hours not steaming is estimated as the difference between 730 and the sum of hours steaming underway and hours steaming not underway.

### The Effects of Steaming on Readiness

Fleet readiness has three dimensions: (1) crew experience (Training Readiness), (2) equipment condition (Material Readiness), and (3) manning levels (Personnel Readiness). While a particular ship's manning might be affected by steaming, it is unlikely that the personnel readiness of the fleet would be changed. A decline in steaming, however, may affect the fleet's training and material readiness.

Training readiness may be affected most seriously because it is developed through exercises undertaken while steaming:

"The ultimate in training readiness is achieved by realistic exercises, which approximate as close as possible combat conditions. Advanced exercises usually require special facilities such as ranges for live firing, air combat maneuvering, special electronic services, or target services such as operating submarines and drone aircraft."

Equipment condition also may be changed by steaming, but the effect is unclear (and probably less important). It is usually felt that steaming would improve equipment condition because of less wearout; however, many positive and negative factors could be affected which makes the total effect unclear. For example, by reducing the crews' skill in using complex equipment, less steaming could cause more operator induced equipment failures. The net effect of less steaming depends on whether positive effects on factors such as wearout outweigh negative effects on factors such as operators' competence.

How much should steaming be curtailed as the price of fuel increases? In theory the procedure for answering this question is simple. The effects of steaming should be compared with alternative ways of allocating funds to achieve readiness. Resource reductions should be made in activities yielding the least improvements in readiness relative to costs. In reality this procedure is difficult to follow because there is little evidence on the costs of steaming and its effects on readiness.

### Aim of the Present Analysis

Our aim is to estimate the effects of steaming on equipment condition and fuel consumption. Lack of data prevents us from studying the relationship between training readiness and steaming. We focus on the relationship between steaming and equipment condition because data are available to study it.

### Data

A casualty report or CASREPT is filed when a ship has an equipment failure which degrades its mission performance capability for more than four days. Previous studies have concluded that CASREPT downtime is an important indicator of equipment condition, so CASREPT data are used to measure it.<sup>1</sup>

Data on CASREPTs had been obtained for 91 destroyers, cruisers, and frigates for the ship's cycle that ended after January 1970. The data are from the Consolidated CASREPT Reporting System. The sample includes observations on 10,000 C2 and 4,000 C3 and C4 CASREPTs for the period January 1970-July 1975.

Monthly data on steaming and fuel consumption were obtained from the Navy's Steaming and Fuel Data Master File. They consist of observations on about 2,400 ship-months between January 1967 and June 1975.

Since data are on destroyers, cruisers and frigates, findings pertain particularly to these types of ships.

### Estimating Steaming's Effects on CASREPT Downtime

CASREPT downtime per month depends on the monthly CASREPT rate (C) and downtime per CASREPT. Downtime per CASREPT consists of two components: (1) supply time (S), the period a CASREPT is deferred for parts, and (2) maintenance time (M), the period a CASREPT is deferred for administrative delays and actual hands-on repairs.

About 50 percent of CASREPTs occur because parts are unavailable within four days of the equipment's failure.<sup>2</sup> These are called "parts CASREPTs." Downtime first would consist of time waiting for parts, i.e., supply time, and then maintenance time.

---

<sup>1</sup>See Horowitz, Stanley, and Allan Sherman, "Crew Characteristics and Ship Condition," March 1977, CNS 1090; and P.M. Sprey, et al., "Analysis of FF 1052 Availability Experience: Phase I Report," American Management Systems, July 1977.

<sup>2</sup>See table 10.

The other 50 percent of CASREPTs occur because the crew does not have the required expertise or tools to repair the broken equipment; in these cases downtime is all maintenance time. Equipment is repaired with assistance of other "repair echelons" such as a tender ship (IMA), a shipyard, or an expert who is brought to the ship.<sup>1</sup>

Through a literature review and discussions with Navy personnel, "reduced form" regression models for C, S, and M are specified which include current and past steaming and other factors as explanatory variables. These are derived from "structural models" relating C, S, and M to "direct determinants." In deriving regression models, we find in theory a regression variable could affect numerous direct determinants which have different effects qualitatively. Unfortunately this makes it impossible to identify the causal links through which a regression variable operates. The upshot is that although we estimate steaming reduces CASREPT downtime, we cannot tell from the data why it has this beneficial effect.

Previous studies suggest that a few CASREPTs have extremely long supply and maintenance times.<sup>2</sup> Since the distributions of S and M have a long tail, we regress the logarithm of S and M on regression variables.<sup>3</sup> A linear model is used to analyze the monthly CASREPT rate. Given estimates of steaming's effects on C, S, and M, we calculate its effects on CASREPT downtime.

Lack of data is a serious problem which is addressed in a number of ways. Numerous proxy variables are used (such as current and past steaming) for causal factors (such as current and past equipment utilization).<sup>4</sup> Separate models are estimated for different subgroups, i.e., type of CASREPT and ship class. The important CASREPT rate relationship is estimated using different estimation procedures, i.e., OLS and LSDV, and data sets, i.e., pooled time series cross section and cross section.

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<sup>1</sup>A CASREPT could also occur if administrative delays prevent equipment from being repaired within four days. This is a more likely possibility for C2 than C3/C4 CASREPTs.

<sup>2</sup>See S.D. Vesco, "A Study of Mean Supply Response Time," Search Report 6, 26 January 1970, pp. 23-32.

<sup>3</sup>We also regressed the level of S and M on regression factors. The logarithm models fit the data better.

<sup>4</sup>There is no way to be sure we have observed a causal rather than spurious relationship between steaming and CASREPT downtime. Two alternative explanations are analyzed.

### Estimating Steaming's Effect on Fuel Consumption

We identify six factors affecting fuel consumption, including (1) hours steaming underway, (2) hours steaming not underway, (3) steaming speed, (4) environmental conditions, (5) ship size and (6) efficiency of plant. Our goal is to estimate the effects of steaming underway holding other factors fixed; however, this is difficult to do because data are not readily available on most factors besides (1) and (2).

Fuel consumption per ship-month is specified to be a quadratic function of steaming underway and steaming not underway. A quadratic function is used so that we could allow for nonlinear relationships. This regression model is estimated separately for diesel, JP5, and "other" fuel. Estimates of increases in fuel consumption for each fuel are evaluated at October 1977 prices and added to yield the marginal cost of steaming underway.

A separate analysis is done for each ship class (13) to adjust for differences in ship size and efficiency of plant. Data are unavailable on environmental conditions and steaming speed, which would not be a problem except that there might be a relationship between these factors and steaming. For example, hours steaming may decline as ship's speed is increased. Estimates of marginal fuel costs assume such relationships, if any, continue to hold in the future as they did in the regression period.

Historically, as hours steaming underway declined there was a one-for-one increase in hours not steaming. We assume this relationship holds when calculating the tradeoff between CASREPT downtime and fuel costs. The sensitivity of our findings to this assumption is analyzed in the final section.

## ANALYSIS OF STEAMING'S EFFECTS ON CASREPT DOWNTIME AND ITS COMPONENTS

### CASREPT RATE

#### Regression Model Specification

Direct determinants of the CASREPT rate are listed below together with the expected direction of their effects.

1. Past utilization of equipment (+)
2. Current utilization of equipment (+)
3. Age of equipment (+)
4. Degree of equipment complexity (+)
5. External conditions (-)
6. Condition of equipment after overhaul (-)
7. Training of personnel (-)
8. Number of equipment starts (+)
9. Initial stock of parts on board (-)
10. OPTAR funds allowance (-)
11. Willingness of command to report CASREPTs (+)

Data are unavailable on most of these determinants. To overcome data problems, we identified relationships between them and measurable explanatory variables, which are given below. If we could identify it, the direction of an explanatory variable's effect on a direct determinant is indicated.

1. Past utilization of equipment (+):  
Past steaming underway (+)  
Past steaming not underway (+)  
Time since overhaul (+)
2. Current utilization of equipment (+):  
Current steaming underway (+)  
Current steaming not underway (+)
3. Age of equipment (+):  
Months since overhaul (+)
4. Degree of equipment complexity (+):  
Ship class (?)
5. Favorable external conditions (-):  
No measurable explanatory variables identified

6. Good condition of equipment after overhaul (-):  
Atlantic or Pacific Fleet (?)
7. Training of personnel (-):  
Current steaming underway (+)  
Current steaming not underway (+)  
Past steaming underway (+)  
Past steaming not underway (+)  
Time since overhaul (+)
8. Number of equipment starts (+):  
No data available
9. Stock of parts on board (-):  
Fleet (?)  
Time since overhaul (-)
10. OPTAR funds allowance (-):  
Fleet (?)
11. Willingness of command to report CASREPTS (+):  
Fleet (?)  
Point in the deployment cycle:  
Months 1,2,3 and 4 after overhaul (+)  
Months 1,2,3 and 4 prior to overhaul (-).

This system of structural relationships was solved in terms of measurable explanatory variables. The result is a reduced form regression model having the variables listed in table 2. We also include "number of months since Jan 1970" to test for time trends.

By specifying theoretical relationships, we are able to identify explanatory variables, such as past and current steaming, that may affect the CASREPT rate. However, except for the dummy variables, months 1, 2, 3 and 4 after and before overhaul, the direction of a regression variable's effect cannot be predicted a priori, a result which may not critically depend on our particular specification of relationships between explanatory variables and determinants.<sup>1</sup> Signs of regression variables are ambiguous because each is related to several direct determinants which have different effects qualitatively. These real world complexities make it impossible to understand the reasons for the measured effect of a regression variable. Thus, although steaming reduces the CASREPT rate, one cannot explain how it achieves this beneficial effect.

---

<sup>1</sup>An alternative system of relationships probably also would yield ambiguous theoretical results.

TABLE 2

DEFINITIONS, MEAN VALUES AND STANDARD DEVIATIONS OF  
CASREPT RATE MODEL VARIABLES

Variables	Mean values	Standard deviations
Monthly number C2 CASREPTs	4.14	3.61
Monthly number C3/C4 CASREPTs	1.55	1.89
Monthly steaming hours underway	247.84	197.2
Total past steaming hours underway since overhaul	5576.7	2996.5
Monthly steaming hours not underway	139.4	131.2
Total past hours steaming not underway since overhaul	3653.0	2306.4
Number of months since Jan 1970	20.4	12.3
Number of months since overhaul	22.1	12.0
Overhaul cycle variables:		
One if first month after overhaul, zero otherwise	0.016	.12
One if second month after overhaul, zero otherwise	0.017	.13
One if third month after overhaul, zero otherwise	0.017	.13
One if fourth month after overhaul, zero otherwise	0.017	.13
One if first month before overhaul, zero otherwise	0.034	.18
One if second month before overhaul, zero otherwise	0.034	.18
One if third month before overhaul, zero otherwise	0.034	.18
One if fourth month before overhaul, zero otherwise	0.033	.18
Ship classes:		
FRAMS: Benchmark ship class	0.32	N.A.
DD 931	0.079	.27
DDG 2	0.18	.38
DDG 31	0.019	.14
DDG 35	0.018	.13
DDG 40	0.0073	.085
FF 1036 One if in ship class, zero otherwise	0.0073	.085
FF 1037	0.073	.26
FF 1040	0.095	.29
FF 1052	0.041	.20
FPG 1	0.026	.16
CG 16	0.049	.22
CG 26	0.084	.28
Fleet: One if Atlantic, zero otherwise	0.48	.50

### Findings

Pooled time series cross section data on 2468 ship-months are used to analyze the CASREPT rate for C2 and C3/C4 CASREPTS. Regression results, given in table 3, are obtained using the ordinary least squares estimation procedure.

The F statistics indicate both regressions are statistically significant at the .01 level. The  $R^2$  of 0.140 for C2 and 0.0957 for C3/C4 CASREPTS are low but not unusual for models estimated with time series cross section data. Low  $R^2$  values indicate that about 90 percent of the variation in the CASREPT rate is unexplained. A large fraction of serious equipment failures is still random, but some of it can be explained.

Our major finding is that past steaming has a statistically significant and important beneficial effect on the CASREPT rate. This variable's high t-values of 6.5 for C2 and 4.4 for C3/C4 CASREPTS indicate that the regression coefficients are statistically significant at the .05 level.

The "elasticity" is the percent change in a dependent variable due to a one percent change in an explanatory variable. If the elasticity equals one in absolute value, a variable has a proportional effect. e.g., if x changes by 10 percent y also changes by 10 percent.

Elasticities of past steaming are  $-0.661^1$  for C2 and  $-0.639$  for C3/C4 CASREPTS, indicating there is a less than proportional but substantial effect of past steaming on the CASREPT rate.

Number of months since overhaul has a statistically significant, positive and relatively large effect. The elasticities are 0.688 for C2 and 0.831 for C3/C4 CASREPTS. As months since overhaul increase CASREPTS per month increase; but past steaming also increases which reduces the CASREPT rate. The net effect is to only slightly increase the CASREPT rate by about one C3/C4 CASREPT per year. The implication is that overhauls can be scheduled farther apart without causing serious deterioration of equipment condition.

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<sup>1</sup> Due to rounding, elasticities computed by the reader may differ slightly from those reported in the text in this and later sections.

TABLE 3  
CASREPT RATE REGRESSION FINDINGS

Variable	C2		C3/C4	
	Effect <sup>a</sup>	Elasticity <sup>b</sup>	Effect <sup>a</sup>	Elasticity <sup>b</sup>
Current hours steaming underway per month	.00216 <sup>c</sup> (5.7555)	.12923	.00008 (.3912)	.01259
Total past steaming hours underway since overhaul	-.00049 (6.52165) <sup>c</sup>	-.66163	-.00018 (4.3961) <sup>c</sup>	-.63926
Current hours steaming not underway per month	.00143 (2.4533) <sup>c</sup>	.04822	.00104 (3.30056) <sup>c</sup>	.09298
Total past hours steaming not underway since overhaul	-.00013 (1.6323)	-.11474	-.00001 (.2218)	-.02235
Number of months since Jan 1970	-.00205 (.2281)	-.01009	.00128 (.2651)	.01680
Number of months since overhaul	.12909 (5.4296) <sup>c</sup>	.68802	.05842 (4.57923) <sup>c</sup>	.83170
Dummy variables:				
First month after overhaul	1.11332 (1.9553) <sup>c</sup>		.45678 (1.4950)	
Second month after overhaul	.06988 (.1264)		.27744 (.9356)	
Third month after overhaul	-.29071 (.5324)		.03801 (.1297)	
Fourth month after overhaul	-.07861 (.1452)		-.28703 (.9882)	

TABLE 3 (Cont'd)

Variables	C2		C3/C4	
	Effect <sup>a</sup>		Effect <sup>a</sup>	
First month before overhaul	-2.11825 (5.2371) <sup>c</sup>		-.83522 (3.84576) <sup>c</sup>	
Second month before overhaul	-1.07911 (2.7201) <sup>c</sup>		-.47636 (2.23779) <sup>c</sup>	
Third month before overhaul	-.73260 (1.8687) <sup>c</sup>		-.58172 (2.76527) <sup>c</sup>	
Fourth month before overhaul	-.50262 (1.2795)		-.11158 (.5483)	
DD 931	1.81859 (6.6534) <sup>c</sup>		.00901 (.0615)	
DDG 2	1.23585 (5.3998) <sup>c</sup>		.05894 (.4799)	
DDG 31	.76626 (1.4101)		-.19032 (.6527)	
DDG 35	.88488 (1.6495)		.27104 (.9415)	
DDG 40	-2.20916 (2.4353) <sup>c</sup>		-1.23961 (2.5468) <sup>c</sup>	
FP 1036	.84500 (1.0307)		-.62049 (1.4104)	

TABLE 3 (Cont'd)

Variable	C2		C3/C4	
	Effect <sup>a</sup>		Effect <sup>a</sup>	
FF 1037	-.83358 (2.5547) <sup>c</sup>		-.03722 (.2126)	
FF 1040	-.83242 (2.7964) <sup>c</sup>		-.10882 (.6813)	
FF 1052	-.95217 (2.3698) <sup>c</sup>		.84612 (3.92438) <sup>c</sup>	
FFG 1	1.27900 (2.686) <sup>c</sup>		1.16820 (4.57256) <sup>c</sup>	
CG 16	1.55460 (4.3856) <sup>c</sup>		.28217 (1.4834)	
CG 26	1.00975 (3.5855) <sup>c</sup>		.36707 (2.42908) <sup>c</sup>	
Fleet	.092258 (5.60658) <sup>c</sup>		.61665 (6.98373) <sup>c</sup>	
Constant	3.11445		.76700	
Summary Statistics F(27,2440)	14.76114		9.57391	
R <sup>2</sup>	.14041		.09579	

Sources: Steaming and Fuel Data Master Files and Consolidated CASREPT Reporting Systems

<sup>a</sup> - values given in parentheses.

<sup>b</sup> - calculated at the arithmetic means.

<sup>c</sup> - statistically significant at .05 level.

With respect to other variables, more current steaming hours underway per month increases both C2 and C3/C4 CASREPTs, but the effect is statistically significant only for C2 CASREPTs. The elasticities are relatively low, 0.129 (C2) and 0.0125 (C3/C4). Current steaming hours not underway has a positive, relatively small but statistically significant effect on both C2 and C3/C4 CASREPTs. Total past steaming not underway may decrease both C2 and C3/C4 CASREPTs. These effects are small and not statistically significant.

Atlantic fleet ships have statistically more C2 and C3/C4 CASREPTs than those in the Pacific fleet. Overhaul cycle variables indicate the CASREPT rate is higher in the first and perhaps second months after overhaul, so that overhauls may not fix everything they are supposed to. By contrast, CASREPT rates are lower for the last three to four months before overhaul. Perhaps temporary repairs are made more often towards the end of a cycle with the expectation that permanent repairs will be made during the overhaul.

In summary, although the explanatory power of the CASREPT rate regression models is low, a number of variables are statistically significant. Our most important findings are that past steaming and time since overhaul have large effects and Atlantic fleet ships have higher CASREPT rates.

#### MAINTENANCE DOWNTIME PER CASREPT

##### Regression Model Specification

Direct determinants of maintenance per CASREPT are listed below together with the expected direction of their effects.

1. Operating demands for ship maintenance (+)
2. Quality and quantity of ship's maintenance personnel (-)
3. Whether CASREPT for parts (-)
4. Degree of equipment complexity (·)
5. Technical difficulty of required maintenance (+)
6. Supply of intermediate level maintenance resources (-)
7. Supply of ship's other maintenance resources (-)
8. Whether repaired off ship (+)
9. Whether period of overhaul quality control (+)<sup>1</sup>

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<sup>1</sup>Just after an overhaul there may be a quality control period during which personnel spend extra time repairing CASREPTs.

As in the CASREPT rate analysis, to overcome data problems we identified relationships between direct determinants and measurable explanatory variables which are given below. If we could identify it, the direction of an explanatory variable's effect on the direct determinant is indicated.

1. Operating demands for maintenance personnel (+):
  - Current steaming underway (+)
  - Past steaming underway (-)
  - Current steaming not underway (+)
  - Past steaming not underway (-)
  - Whether a C3/C4 CASREPT (-)
2. Supply of maintenance personnel (-):
  - Past steaming underway (+)
  - Current steaming underway (+)
  - Past steaming not underway (+)
  - Current steaming not underway (?)
  - Time since overhaul (+)
  - Whether C3/C4 CASREPT (+)
3. Whether CASREPT for parts (-):
  - Measured directly by whether a CASREPT had any supply downtime
4. Degree of equipment complexity (+):<sup>1</sup>
  - Past steaming underway (?)
  - Past steaming not underway (?)
  - Repair echelon (?)
  - Ship class (?)
  - Time since overhaul (?)
5. Technical difficulty of required maintenance (+):
  - Current steaming underway (?)
  - Current steaming standing still (?)
  - Repair echelon (?)
  - Ship class (?)
  - Time since overhaul (?)
6. Supply of intermediate level maintenance resources (-):
  - Fleet (?)
7. Supply of ship's other maintenance resources (e.g., diagnostic equipment, etc.) (-):
  - No explanatory variable identified

---

<sup>1</sup>Average equipment complexity depends on the number and mix of CASREPTs among subsystems. We assume it is measured by the factors listed.

8. Repaired off ship (+)  
Repair echelon (+)
9. Whether period of overhaul quality control (+)  
Months 1,2,3 and 4 after overhaul (+)

We solved this system of relationships in terms of measurable explanatory variables. The result is a regression model having the variables listed in tables 4 and 5. We also include "number of months since January 1970" to test for a time trend.

Except for the dummy variables, whether CASREPT for parts (-), whether a C3/C4 CASREPT (-), and months 1,2,3 and 4 after overhaul (+), the direction of an explanatory variable's effect cannot be predicted, and it is impossible to identify the reasons for its effect on maintenance downtime.

The distribution of maintenance downtime has a "long tail" -- a few maintenance actions take a long time. The time for most is clustered around the geometric rather than the arithmetic mean. Because of the distribution's skewness, the natural logarithm rather than the actual level of maintenance downtime per CASREPT is regressed on explanatory variables.<sup>1</sup>

#### Findings

Pooled time series cross section data on 10,225 C2 and 3,895 C3/C4 CASREPTs are used to analyze maintenance downtime per CASREPT. Regression results, given in table 6, are obtained using the ordinary least squares estimation procedure.

The F statistic indicates the regression is statistically significant at the .01 level. The  $R^2$  of 0.243 for C2 and 0.107 for C3/C4 CASREPTs indicate a small proportion of the variation in maintenance downtime per CASREPT is explained by our variables.

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<sup>1</sup> Although not reported, we also estimate the model using the actual level of maintenance downtime per CASREPT. As expected the log model provided a better fit. For discussion of the statistical procedure used to determine which model better fit the data, see Rao, P. and Miller, R.L., Applied Econometrics (Wadsworth: Belmont, Calif., 1971) pp. 107-III.

TABLE 4

DEFINITIONS, MEAN VALUES AND STANDARD DEVIATIONS OF  
C2 MAINTENANCE DOWNTIME MODEL VARIABLES

Variables	Mean values	Standard deviations
Hours of C2 CASREPT downtime due to maintenance	540.8	1089.7
Ratio of hours steaming underway to CASREPT's maintenance downtime	.318	.249
Total hours of past steaming before CASREPT (in thousands)	5.054	2.902
Ratio of hours steaming not underway to CASREPT's maintenance downtime	.198	.174
Total hours of past steaming not underway before CASREPT (in thousands)	3.545	2.249
Months since Jan 1970	19.4	11.8
Months since overhaul	20.8	11.7
The following are dummy variables:		
If there was any downtime due to supply = 1	.54	.50
Ship classes:		
FRAM: Benchmark class	.29	N.A.
DD 931	.10	.31
DDG 2	.21	.41
DDG 31	.018	.13
DDG 35	.019	.14
FF 1036	.0026	.051
FF 1037	.0074	.086
FF 1040	.058	.23
FF 1052	.074	.26
FFG 1	.028	.16
DDG 40	.031	.17
CG 16	.063	.24
CG 26	.092	.29
Repair echelon:		
Repair by ship's crew is benchmark echelon	.55	N.A.
If repaired with technical assistance = 1	.19	.39
If repaired at IMA = 1	.26	.44
If repaired at overhaul = 1	.0014	.037
If repaired at drydock = 1	.0020	.044
Months since overhaul dummy variables:		
One month after overhaul	.0015	.038
Two months after overhaul	.0020	.044
Three months after overhaul	.0020	.044
Four months after overhaul	.0025	.050
Fleet: 1 if Atlantic, 0 if Pacific	.52	.50
Geometric mean = 143.897		

TABLE 5

DEFINITIONS, MEAN VALUES AND STANDARD DEVIATIONS OF  
C3/C4 MAINTENANCE DOWNTIME MODEL VARIABLES

Variables	Mean values	Standard deviations
Hours of C3/C4CASREPT downtime due to maintenance	361.0	735.5
Ratio of hours steaming underway to maintenance downtime (current steaming underway)	.303	.243
Total hours of steaming in months before CASREPT (in thousands)	5.325	2.970
Ratio of hours steaming not underway to maintenance downtime (current steaming not underway)	.197	.177
Total hours of steaming not underway in months before CASREPT (in thousands)	3.747	2.401
Months since Jan 1970	20.29	12.3
Months since overhaul	22.25	12.4
The following are dummy variables:		
If there was any downtime due to supply = 1	.51	.50
Ship classes:		
FRAM: Benchmark class	.32	N.A.
DD 931	.078	.27
DDG 2	.18	.38
DDG 31	.0098	.098
DDG 35	.018	.13
FF 1036	.0005	.022
FF 1037	.0023	.048
FF 1040	.071	.26
FF 1052	.077	.27
FFG 1	.051	.22
DDG 40	.046	.21
CG 16	.058	.23
CG 26	.094	.29
Repair echelon:		
Repair by ship's crew is benchmark echelon	.48	N.A.
If repaired with technical assistance = 1	.23	.42
If repaired at IMA = 1	.28	.45
If repaired at overhaul = 1	.0018	.042
If repaired at drydock = 1	.0008	.028
Months since overhaul dummy variables:		
One month after overhaul	.0015	.039
Two months after overhaul	.0023	.048
Three months after overhaul	.0021	.045
Four months after overhaul	.0010	.032
Fleet: 1 if Atlantic, 0 if Pacific	.57	.50
Geometric mean = 111.933		

TABLE 6

## MAINTENANCE REGRESSION FINDINGS

Variable	CASREPTS			
	Effect <sup>a</sup>	Elasticity <sup>b</sup>	Effect <sup>a</sup>	Elasticity <sup>b</sup>
			C2	C3/C4
Ratio of hours steaming underway to maintenance downtime	-.67988 (10.8291) <sup>c</sup>	-.21361	-1.10619 (10.6640) <sup>c</sup>	-.3218
Total hours of steaming underway before CASREPT	.02722 (1.6313)	.13757	.11828 (4.4039) <sup>c</sup>	.6298
Ratio of hours steaming not underway to maintenance downtime	-.51621 (5.4626) <sup>c</sup>	-.10195	-.37973 (2.4669) <sup>c</sup>	-.0748
Total hours of steaming not underway before CASREPT	.02257 (1.2849)	.08003	.01206 (.4370)	.0452
Months since Jan 1970	.00632 (3.2653) <sup>c</sup>	.12280	.00157 (.4827)	.0318
Months since overhaul	-.00650 (1.2013)	-.13546	-.02142 (2.6342) <sup>c</sup>	-.4765
Dummy variables:				
If any downtime due to supply = 1	-1.33249 (41.5056) <sup>c</sup>		-1.01228 (19.9845) <sup>c</sup>	
Ship class:				
DD 931	.15594 (2.8844) <sup>c</sup>		.14717 (1.5208)	
DDG 2	-.14306 (2.9367) <sup>c</sup>		-.13436 (1.6205)	

TABLE 6 (Cont'd)

Variable	CASREPTS	
	C2	C3/C4
	Effect <sup>a</sup>	Effect <sup>a</sup>
DDG 31	-.28042 <sup>c</sup> (2.3065)	-.32662 (1.2845)
DDG 35	-.13927 (1.2235)	.32846 (1.7393)
FF 1036	-.19724 (.6535)	-.87681 (.8246)
FF 1037	-.19675 (1.1090)	-.21466 (.4278)
FF 1040	-.00973 (.1265)	.11844 (1.0368)
FF 1052	.05546 (.7912)	-.16780 (1.4960)
FFG 1	-.08412 (.8325)	-.21390 (1.6195)
DDG 40	.16956 (1.7297)	.06251 (.4505)
CG 16	-.22091 <sup>c</sup> (3.1067)	-.07222 (.6091)
CG 26	-.05083 (.8201)	-.20530 <sup>c</sup> (2.1059)

TABLE 6 (Cont'd)

Variable	CASREPTS	
	C2	C3/C4
Repair echelon: Technical assistance	.39163 <sup>c</sup> (9.6473)	.52283 <sup>c</sup> (8.5469)
IMA	.49122 <sup>c</sup> (13.0443)	.52660 <sup>c</sup> (8.7273)
Overhaul	.69615 (1.7389)	.26901 (.4764)
Drydock	2.11088 <sup>c</sup> (6.2956)	1.56509 (1.8177)
Months after overhaul dummy variables: One month after overhaul	.55523 (1.4328)	.41466 (.6768)
Two months after overhaul	.08933 (.2664)	-.16197 (.3240)
Three months after overhaul	-.21190 (2.000)	-.08436 (.1581)
Four months after overhaul	-.07052 (.2387)	1.96058 <sup>c</sup> (2.6312)
Fleet: 1 if Atlantic, 0 if Pacific	.05236 (1.4335)	.04801 (.8062)

TABLE 6 (Cont'd)

Variable	C2		C3/C4	
	Effect <sup>a</sup>		Effect <sup>a</sup>	
Constant	5.70227		5.15632	
Summary statistics:				
$F$	$F(28,10196) = 117.21770$		$F(28,3866) = 36.0933$	
$R^2$	.24351		.20724	

Sources: Steaming and Fuel Data Master Files and Consolidated CASREPT Reporting Systems.  
<sup>a</sup>t-values given in parentheses.

<sup>b</sup>calculated at the geometric means of maintenance downtime per CASREPT and arithmetic mean of explanatory variables.

<sup>c</sup>Statistically significant at the .05 level.

Steaming prior to the opening date of the CASREPT, past steaming, increases maintenance downtime, but the effect is statistically significant only for C3/C4 CASREPTs. The elasticities are 0.137 for C2 and 0.629 for C3/C4 CASREPTs.

To measure steaming intensity during the life of a CASREPT, which could be days, weeks, or months, we divided steaming hours during the CASREPT's maintenance period by maintenance time. The ratio of a CASREPT's maintenance downtime spent steaming underway, "current steaming," has a negative and statistically significant effect for both C2 and C3/C4 CASREPTs. The elasticities are -0.213 for C2 and -0.321 for C3/C4 CASREPTs.

Past steaming not underway increases maintenance downtime but current steaming not underway reduces it. Elasticities are 0.10 or less for C2 and C3/C4 CASREPTs, so these variables have small effects on maintenance downtime.

The dummy variable "if any downtime due to supply" has a statistically significant and negative sign for C2 and C3/C4 CASREPTs. Thus if the CASREPT had to wait for parts, its maintenance downtime was substantially less than if the equipment was down for other reasons.

The positive signs of technical assistance and IMA are statistically significant, indicating that CASREPTs have longer maintenance times if they are repaired off the ship. Drydock is statistically significant only for C2 CASREPTs, probably because the extremely small number of repairs made at that echelon makes it difficult to measure an effect.

Except for the CG 26, ship class variables do not have statistically significant effects for C3/C4 CASREPTs, which indicates that maintenance downtime is about the same for all ship classes as it is for FRAMs. For C2 CASREPTs, however, the DDG 2, DDG 31, CG 16 and CG 26 ship classes have lower maintenance times, while the DD 931 has statistically higher maintenance times compared to FRAMs.

Overhaul dummy variables varied in sign and their effects are small and generally not statistically significant. Atlantic fleet has a positive, small, but not statistically significant effect. Time has a positive effect but it is significant only for C2 CASREPTs.

To test whether C3/C4 CASREPTs had less maintenance downtime than C2 CASREPTs, we pool the data and include a dummy variable for C3/C4 CASREPTs. The results indicate that C3/C4 CASREPTs have less maintenance downtime. The effect is statistically significant at the .05 level. These results may be because of shorter administrative delay times for C3/C4 CASREPTs.

In summary, the regression model is statistically significant, but it explains only a small percent of the variation in maintenance downtime per CASREPT. Past steaming underway and past steaming not underway increase maintenance downtime, while current steaming underway and current steaming not underway reduce it. Maintenance time was much lower for CASREPTs that had to wait for parts and for C3/C4 CASREPTs. Time since overhaul has an adverse effect, and CASREPTs repaired off ship also had more maintenance time. While ship classes had some effects, fleet and cycle dummy variables had none. Finally, maintenance downtime seems to be increasing over time.

#### SUPPLY DOWNTIME PER CASREPT

##### Regression Model Specification

As in the previous two subsections, direct determinants are listed first together with the expected direction of their effects.

1. Parts required per CASREPT (+)
2. Amount of parts reordering (+)
3. Inventory of parts stocked by suppliers (-)
4. Frequency of deliveries from suppliers (-)
5. Availability of funds for repair parts (-)

Again, to overcome data problems we identified relationships between direct determinants and measurable factors. These are given below.

1. Parts required per CASREPT (+):
  - Past steaming underway (?)
  - Past steaming not underway (?)
  - Ship class (?)
  - Time since overhaul (?)
2. Amount of parts reordering (+):
  - Past steaming underway (?)
  - Repair echelon (?)
  - Past steaming not underway (?)
  - Ship class (?)
  - Time since overhaul (?)

Current steaming underway (?)  
Current steaming not underway (?)  
Whether C3/C4 CASREPT (-)

3. Inventory of parts stocked by suppliers (-):  
Ship class (?)  
Fleet (?)
4. Frequency of deliveries from suppliers (-):  
Current steaming underway (-)  
Fleet (?)  
Whether C3/C4 CASREPT (+)
5. Special parts requirements (+):  
Repair echelon (?)  
Ship class (?)

We solved this system of structural relationships to yield the reduced form regression models listed in tables 7 and 8. We also include the logarithm of the number of months since January 1970 to test for a time trend.

Although a C3/C4 CASREPT should have fewer hours of supply downtime, the direction of other variable effects could not be predicted. As before, by specifying theoretical relationships we can identify explanatory variables but not the direction of their effects a priori, and we cannot explain the reason for a regression variable's measured effect.

Like maintenance downtime, the distribution of supply downtime has a "long tail" -- a few take a long time. The time for most is clustered around the geometric rather than the arithmetic mean. Because of the skewness of the distribution, the natural logarithm rather than the actual level of supply downtime per CASREPT is regressed on explanatory variables.<sup>1</sup>

#### Findings

Pooled time series cross section data on 6,008 C2 and 2,110 C3/C4 CASREPTs are used to analyze supply downtime. Regression

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<sup>1</sup>Although not reported, we also estimate the model using the actual level of supply downtime per CASREPT. As expected, the log model provided a better fit, although neither model fit the data well. For a discussion of the statistical procedure used to determine which of these models fit the data better, see Rao and Miller, op cit., pp. 107-111.

TABLE 7

DEFINITIONS, MEAN VALUES AND STANDARD DEVIATIONS OF  
C2 SUPPLY TIME MODEL VARIABLES

Variables	Mean values	Standard deviations
Hours of C2 CASREPT downtime due to supply	611.0 <sup>a</sup>	835.8
Ratio of hours steaming underway to CASREPT downtime	.361	.235
Total hours of past steaming before CASREPT (in thousands)	3.325	2.575
Ratio of hours steaming not underway to CASREPT downtime	.226	.150
Total hours of past steaming not underway before CASREPT (in thousands)	2.211	1.474
Logarithm of months since Jan 1970	2.7	.90
Months since overhaul	15.3	8.53
Ship classes:		
FRAM: Benchmark class	.27	N.A.
DD 931	.10	.30
DDG 2	.21	.41
DDG 31	.018	.13
DDG 35	.018	.13
FF 1036	.0025	.050
FF 1037	.0050	.070
FF 1040	.060	.24
FF 1052	.062	.24
FFG 1	.026	.16
DDG 40	.031	.17
CG 16	.077	.27
CG 26	.11	.32
Repair echelon:		
Repair by ship's crew is benchmark echelon	.71	N.A.
If repaired with technical assistance = 1, 0 otherwise	.15	.36
If repaired at IMA = 1, 0 otherwise	.14	.35
If repaired at overhaul = 1, 0 otherwise	.0005	.022
Fleet: 1 if Atlantic, 0 otherwise	.56	.50

<sup>a</sup>Geometric mean of supply time per CASREPT is 311.0, substantially fewer hours than the average of 611.0.

TABLE 8

DEFINITIONS, MEAN VALUES AND STANDARD DEVIATIONS OF  
C3/C4 SUPPLY TIME MODEL VARIABLES

<u>Variables</u>	<u>Mean values</u>	<u>Standard deviations</u>
Hours of C3/C4 CASREPT downtime due to supply	454.1 <sup>a</sup>	679.6
Ratio of hours steaming underway to CASREPT downtime	.339	.235
Total hours of past steaming before CASREPT (in thousands)	3.761	2.558
Ratio of hours steaming not underway to CASREPT downtime	.213	.145
Total hours of past steaming not underway before CASREPT (in thousands)	2.458	1.666
Logarithm of months since Jan 1970	2.80	.80
Months since overhaul	17.2	9.5
Ship classes:		
FRAM: Benchmark class	.28	N.A.
DD 931	.056	.23
DDG 2	.17	.38
DDG 31	.0076	.086
DDG 35	.021	.14
FF 1036	.0009	.030
FF 1037	.0014	.038
FF 1040	.080	.27
FF 1052	.066	.24
FFG 1	.049	.21
DDG 40	.048	.21
CG 16	.068	.25
CG 26	.13	.34
Repair echelon:		
Repair by ship's crew is benchmark echelon	.61	N.A.
If repaired with technical assistance = 1, 0 otherwise	.21	.41
If repaired at IMA = 1, 0 otherwise	.16	.37
If repaired at overhaul = 1, 0 otherwise	.0014	.037
Fleet: 1 if Atlantic, 0 otherwise	.62	.48

<sup>a</sup>Geometric mean of supply time per CASREPT is 224.1, substantially fewer hours than the average of 454.1.

results, given in table 9, are obtained using the ordinary least squares estimation procedure.

The models explain almost none of the variation in supply downtime. Although they are statistically significant relationships, the  $R^2$  is only 0.0239 for C2 and 0.0216 for C3/C4 CASREPTs.

For C3/C4 CASREPTs only dummy variables for three ship classes and Atlantic fleet are statistically significant. C2 CASREPTs, current steaming not underway, time, six ship classes, IMA, and Atlantic fleet are statistically significant. The time trend variable, logarithm of months since January 1970, has a significant negative effect for C2 CASREPTs, but a positive and not significant effect for C3/C4 CASREPTs.

Current and past steaming underway slightly reduce supply time for C2 CASREPTs; for C3/C4 CASREPTs their effects are small and in opposite directions. Current and past steaming not underway reduce supply time for all CASREPTs.

To test whether C3/C4 CASREPTs had less supply downtime, we pool the data and include a dummy variable for C3/C4 CASREPTs. The results indicate that C3/C4 CASREPTs have less supply downtime. The impact is statistically significant at the .05 level. These results may be because parts are shipped more quickly for C3/C4 CASREPTs.

Perhaps our most interesting finding is the positive sign of Atlantic fleet, which is statistically significant for both C2 and C3/C4 CASREPTs. From the CASREPT rate analysis, we find Atlantic fleet ships had more CASREPTs. To see if this is because of supply problems, we look at the simple correlation between the variables "whether CASREPT for parts" (from the maintenance time regression model) and Atlantic fleet. We find a positive correlation of 0.08, which indicates that Atlantic fleet ships had relatively more CASREPTs because parts were unavailable than did ships in the Pacific fleet.

In summary, supply time seems to be largely unaffected by explanatory variables. Although C3/C4 CASREPTs have less supply downtime, most explanatory factors are not significant. We do find evidence, however, that Atlantic fleet ships have more downtime because of supply related factors.

TABLE 9  
SUPPLY TIME REGRESSION FINDINGS

Variable	CASREPTS			
	C2		C3/C4	
	Effect <sup>a</sup>	Elasticity <sup>b</sup>	Effect <sup>a</sup>	Elasticity <sup>b</sup>
Ratio of hours steaming underway to CASREPT downtime	-.07168 (.9843)	-.02586	-.15834 (1.2487)	-.05368
Total hours of past steaming before CASREPT	-.00000 (.1238)	-.00000	.05000 (1.6684)	.18807
Ratio of hours steaming not underway to CASREPT downtime	-.00451 (4.1827) <sup>c</sup>	-.00102	-.33135 (1.7983)	-.07057
Total hours of past steaming not underway before CASREPT	-.01719 (.3238)	-.0380	-.7000 (1.8344)	-.17205
Logarithm of months since Jan 1970 <sup>d</sup>	-.00217 (2.5218) <sup>c</sup>	-.00217	.05603 (.8974)	.05603
Months since overhaul	.00040 (.0619)	.00613	-.00309 (.2966)	-.05327
Dummy variables:				
Ship classes:				
DD 931	.16575 (2.7471) <sup>c</sup>		-.06950 (.5373)	
DDG 2	-.05885 (1.1617)		-.5591 (.6073)	
DDG 31	.29846 (2.2557) <sup>c</sup>		.23994 (.7109)	

TABLE 9 (Cont'd)

Variable	CASREPTS	
	<u>C2</u> Effect <sup>a</sup>	<u>C3/C4</u> Effect <sup>a</sup>
DDG 35	.14450 (1.1292)	.21670 (1.0617)
FF 1036	-.22032 (.6671)	-.68137 (.7434)
FF 1037	-.38052 (1.6217)	.48639 (.6462)
FF 1040	.09626 (1.2631)	-.25320 <sup>c</sup> (2.1328)
FF 1052	.14281 (1.8160)	-.06640 (.5024)
FFG 1	.04844 (.43019) <sup>c</sup>	-.07068 (.4580)
DDG 40	.37744 (3.6764) <sup>c</sup>	.40507 <sup>c</sup> (2.6938)
CG 16	.24812 (3.5067) <sup>c</sup>	.16448 (1.2728)
CG 26	.18639 (2.9499) <sup>c</sup>	.20658 <sup>c</sup> (1.9667)

TABLE 9 (Cont'd)

Variable	CASREPTS	
	<u>C2</u> <sup>a</sup> Effect	<u>C3/C4</u> <sup>a</sup> Effect
Repair echelon: Technical assistance	.00595 (.1289)	.12360 (1.754)
IMA	.19972 <sup>c</sup> (4.1399)	.01617 (.2049)
Overhaul	.20069 (.2738)	-.09413 (.1261)
Fleet: 1 if Atlantic, 0 if Pacific	.017895 <sup>c</sup> (4.47740)	.16651 <sup>c</sup> (2.397)
Constant	5.4387	5.2648
Summary statistics:		
F	F(22, 5985) = 6.66174	F(22, 2087) = 2.10251
R <sup>2</sup>	.02390	.02168

Sources: Steaming and Fuel Data Master Files and Consolidated CASREPT Reporting Systems  
at-values given in parentheses.

bElasticity evaluated at geometric mean for supply time and arithmetic mean for explanatory variables.

cStatistically significant at .05 level.

dUsed logarithm of time variable to reduce multicollinearity with months since overhaul.

## CASREPT DOWNTIME

In the three previous subsections, components of CASREPT downtime are analyzed. We use the following equation to calculate the total effect of steaming on CASREPT downtime with regression outputs given in those sections.

$$\epsilon_{D,UW} = \alpha \epsilon_{SUP,UW} + (1-\alpha) \epsilon_{M,UW} + \epsilon_{CAS,UW} \quad (1)$$

where

- $\epsilon_{D,UW}$  = elasticity of CASREPT downtime with respect to steaming
- $\epsilon_{SUP,UW}$  = elasticity of supply downtime with respect to steaming
- $\epsilon_{M,UW}$  = elasticity of maintenance downtime with respect to steaming
- $\alpha$  = percent of CASREPT downtime due to supply
- $\epsilon_{CAS,UW}$  = elasticity of the CASREPT rate with respect to steaming.

Equation (1) is derived from the identity CASREPT downtime equals the CASREPT rate times the sum of supply and maintenance time per CASREPT, by taking the logarithm of both sides, differentiating with respect to steaming, and rearranging the right side to yield an equation in terms of elasticities.

The percent of downtime because of supply ( $\alpha$ ) is estimated to be 38 percent for C2 and 39 percent for C3/C4 CASREPTs (see table 10). We estimate  $\alpha$ :

$$\alpha = \frac{\left[ \frac{\text{average supply time}}{\text{for parts CASREPTs}} \right] \times \left[ \frac{\text{proportion of CASREPTs}}{\text{requiring parts}} \right]}{\text{expected downtime for all CASREPTs}}$$

Our goal is to estimate the effects of an increase in steaming using estimates of the effects of current and past steaming variables. However, there are an infinite number of ways that a given increase in steaming hours could be distributed over a ship's cycle; and the distribution would affect the value of the past steaming variable at the midpoint of a ship's cycle where we calculate the effects of a change in steaming. To simplify calculations, we assume changes in steaming are proportional to the existing distribution of steaming hours, so that at any point in a ship's cycle, e.g., the midpoint, current and

TABLE 10

CALCULATION OF  $\alpha$ , BY TYPE OF CASREPT

CASREPT	Number of CASREPTs per month (C)	Average hours of supply time for parts CASREPTs (S) <sup>a</sup>	Percent of all CASREPTs needing parts (P)	Average hours of maintenance time for all CASREPTs (M)	Expected hours of downtime for all CASREPTs (D)	Expected total hours of downtime per month Cx D	$\alpha = PS \div D$ (percent)
C2	4.14	611	54.44	541	874	3618	C <sub>2</sub> 38
C3/C4	1.55	454	50.78	362	592	918	C3/C4 39

<sup>a</sup> "Parts CASREPTs" are those requiring parts that were not on board.

Source: Consolidated CASREPT Reporting System.

past steaming change by the same percent due to a change in steaming. Since we have partial elasticities from the same regression, we can simply add the elasticities of the current and past steaming variables to calculate the elasticity of steaming. The interested reader can use the regression findings to calculate the effects of increases in steaming that are distributed in other ways.

The sum of current and past steaming elasticities for the CASREPT rate, supply time and maintenance time are given in table 11. (These were reported earlier in tables 3, 6 and 9.) To calculate steaming's effect, we add the weighted sum of supply time and maintenance time elasticities to the CASREPT rate elasticity. The elasticity of CASREPT downtime with respect to past and current steaming is calculated to be -0.589 for C2 and -0.386 for C3/C4 CASREPTs.

#### ALTERNATIVE EXPLANATIONS OF STEAMING'S EFFECT ON CASREPT DOWNTIME

Steaming seems to reduce CASREPT downtime in the long run by improving levels of direct determinants. However, instead of measuring a causal relationship, the results may be spurious, a mere statistical aberration. In this subsection we analyze two ways that a spurious relationship could have been generated. Tests of the explanations yield no evidence to reject our earlier findings, and, instead, we find evidence that steaming's effect may be greater than reported in the preceding section.

We find the beneficial effect of steaming is largely due to the effect of past steaming on the CASREPT rate. Perhaps this is because some ships are "lemons" and these do less steaming over a ship's cycle. Although low levels of past steaming would be statistically associated with high CASREPT rates, the causality would be reversed.

Another explanation may be omitted factors related to the deployment cycle. Ships steam more when deployed, but then they are also better manned. Better manning rather than steaming could be causing the beneficial effect on the CASREPT rate. A ship's crew may also look for equipment problems before deployment, and when it finds them file CASREPTs. Since these CASREPTs predate the intense steaming of deployment, few CASREPTs per month occur later in a ship's cycle. This could lead to the results we observed that past steaming reduces the CASREPT rate.

TABLE 11  
ELASTICITIES FOR THE SUM OF PAST  
AND CURRENT STEAMING<sup>a</sup>

CASREPT	CASREPT rate (C)	Supply time per CASREPT (S)	Maintenance time per CASREPT (M)	Downtime	
				per CASREPT $\alpha S + (1-\alpha)M$	Total CASREPT downtime
C2	-0.5324 (0.1039)	-0.02586 (0.36077)	-0.07604 (0.0866)	-0.0566 (0.1472)	-0.589 (0.1802)
C3/C4	-0.6267 (0.1489)	0.1344 (0.1206)	0.3080 (0.1462)	0.2407 (0.1008)	-0.386 (0.1798)

Sources: Tables 3, 6, and 9.

<sup>a</sup> Estimates of standard errors are given in parentheses.

These possible explanations of the results are addressed by estimating alternative CASREPT rate models. Earlier we estimated "Model 1" using time series cross section data. To adjust for ship specific factors including lemon ships, we estimate "Model 2," which is Model 1 plus dummy variables for each ship instead of 12 ship classes. These models are estimated with data on 2,500 ship-months.

We also estimate a "Model 3" using 91 cross sectional observations -- one for each ship. Here the average CASREPT rate between overhauls is the dependent variable, and, where applicable, averages of variables in Model 1 are explanatory variables. By averaging variables, Model 3 tends to eliminate the effects of deployment cycle factors.

Table 12 reports estimates of steaming's effect on the CASREPT rate for the three models. For all models, past steaming reduces the number of C2 and C3/C4 CASREPTs; however the effect is statistically significant only for Models 1 and 2. The sums of past and current steaming elasticities are fairly consistent across models:  $-.468$  (Model 2),  $-.533$  (Model 1), and  $-.678$  (Model 3) for C2 CASREPTs; and  $-.460$  (Model 2),  $-.626$  (Model 1), and  $-.891$  (Model 3) for C3/C4 CASREPTs.

In Models 1 and 2 most of steaming's effect is due to a relatively large past steaming elasticity. In Model 3 the elasticity of current steaming ( $-.506$ ) is larger than the elasticity of past steaming ( $-.385$ ), and these effects are not statistically significant for C2 or C3/C4 CASREPTs.

The reason for Model 3's results is that current and past steaming are measuring the same factor -- long-run differences in steaming rates. In Model 3 "current steaming" is average steaming hours per month between overhauls. "Past steaming" is approximately the total number of steaming hours at the midpoint of a ship's cycle. There is little independent variation between these measures, and this "multicollinearity" causes low levels of statistical significance. Nevertheless, the message from Model 3 is the same as that of the others. In the long run steaming reduces the CASREPT rate.

There are some differences in the size of steaming's effects across models. Which estimate is more accurate? Model 2 yielded the lowest effect of steaming. Estimates from Model 1, which are slightly larger, may be better than those from Model 2 because use of numerous ship dummy variables would tend to

TABLE 12  
CASREPT RATE REGRESSION RESULTS FOR STEAMING,  
BY MODEL AND CASREPT

CASREPT	Model	Current steaming	Past steaming	Total elasticity	R <sup>2</sup>	F <sub>N,M</sub>
C2	Class (t) elasticity	0.00216 (5.75) <sup>a</sup> 0.129	-0.00049 (6.52) <sup>a</sup> -0.662	-0.533	0.140	F <sub>27,2440</sub> 14.76
	Ship (t) elasticity	0.00244 (6.79) <sup>a</sup> 0.146	-0.00046 (4.09) <sup>a</sup> -0.614	-0.468	0.254	F <sub>92,237</sub> 8.80
	Cross section (t) elasticity	-0.00355 (0.60) -0.219	-0.00033 (1.22) -0.459	-0.678	0.462	F <sub>19,71</sub> 3.21
	Class (t) elasticity	0.00008 (0.39) 0.013	-0.00018 (4.40) <sup>a</sup> -0.639	-0.626	0.096	F <sub>27,2440</sub> 9.57
	Ship (t) elasticity	0.00014 (0.73) 0.023	-0.00013 (2.19) <sup>a</sup> -0.483	-0.460	0.181	F <sub>92,2375</sub> 5.69
	Cross section (t) elasticity	-0.00308 (1.11) -0.506	-0.00011 (0.82) -0.385	-0.891	0.516	F <sub>19,71</sub> 3.98

Sources: Steaming and Fuel Data Master File and Consolidated CASREPT Reporting System.

<sup>a</sup>statistically significant at .05 level.

bias down the estimate of other variables such as steaming.<sup>1</sup> In Model 1 we use 12 ship class dummy variables to capture long-run differences in the CASREPT rate due to ship class specific factors. This is a compromise approach that may enable us to adjust for some ship specific factors without seriously biasing downward the effects of other included variables such as steaming.

There is a more sizable difference between the steaming elasticities from Model 1 and the larger ones obtained from Model 3, especially for C3/C4 CASREPTs. Predictions from these two models are used to help decide which yields the better estimate of steaming's effect.

Recall that Model 1 focuses on a ship's monthly CASREPT rate, while Model 3 deals with its average number of CASREPTs per month between overhauls. Focusing on different dependent variables, outputs require some adjusting to make predictions comparable. For each ship, we averaged monthly predictions from Model 1 to yield a prediction of a ship's average CASREPT rate per month between overhauls.

Comparison of average CASREPT rate predictions yields evidence in support of Model 3's higher steaming elasticity. The sum of squared errors is somewhat smaller and predictions at the tails are slightly more accurate. Since the evidence is weak, however, we decided to use the more conservative estimate of steaming's effects from Model 1, preferring to avoid possibly overstating its effect.

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<sup>1</sup>See Marc Nerlove, "Further Evidence of the Estimation of Dynamic Economic Relations from a Time Series of Cross Section," Econometrica XXXIX (2): 359-82 (Mar 71).

## ANALYSIS OF STEAMING'S EFFECT ON FUEL CONSUMPTION

### THEORY

We identified direct determinants of fuel consumption, which are listed below together with the expected direction of their effects.

1. Hours steaming underway (+)
2. Hours steaming not underway (+)
3. Ship size (+)
4. Steaming speed (+)
5. Environmental conditions (-)
6. Efficiency of plant (-)

Our goal is to estimate the effect of steaming holding other factors fixed. Data are available on steaming hours not underway, which enables us to hold this factor fixed; and a separate analysis is done for each ship class to adjust for differences in ship size and propulsion system efficiency.

Data are not available on steaming speed and external conditions, which prevents us from holding them fixed. In theory, not adjusting for their effects could bias our estimate of steaming. For example, if ships use greater speed to compensate for a low steaming allowance or if they steam more in better weather, steaming's marginal cost would be understated compared to the cost of a random increase in steaming. In reality the bias is likely to be small and our estimate is accurate as long as relationships, if any, continue to hold.

Regression analysis is used to estimate the elasticity of fuel consumption with respect to steaming. The estimated elasticity should be a fraction because it is approximately equal to the share of total fuel costs due to steaming underway. This can be shown easily.

Let

- $X_1$  = hours not steaming
- $X_2$  = hours steaming underway
- $X_3$  = hours steaming not underway

$C_1$  = fuel costs because of  $X_1$

$C_2$  = fuel costs because of  $X_2$

$C_3$  = fuel costs because of  $X_3$

and  $C$  = total fuel costs.

By definition  $C = C_1 + C_2 + C_3$ . Taking the total differential yields

$$dC = \frac{dC_1}{dX_1} dX_1 + \frac{dC_2}{dX_2} dX_2 + \frac{dC_3}{dX_3} dX_3.$$

Multiplying both sides by  $1/C$  and the  $i^{\text{th}}$  right side

expression by  $\frac{X_i C_i}{X_i C_i}$  for each yields

$$\frac{dC}{C} = \frac{C_1}{C} \frac{dX_1}{X_1} \epsilon_{C_1, X_1} + \frac{C_2}{C} \frac{dX_2}{X_2} \epsilon_{C_2, X_2} + \frac{C_3}{C} \frac{dX_3}{X_3} \epsilon_{C_3, X_3},$$

where  $\epsilon_{C_i, X_i}$  = elasticity of  $C_i$  with respect to  $X_i = 1$ .

(It seems reasonable to assume that fuel costs due to each category of steaming,  $C_i$ , are proportional to the level of steaming in the category  $X_i$ . This implies that the  $\epsilon_{C_i, X_i}$  are each equal to one.)

Assuming that steaming not underway ( $X_3$ ) is unaffected by changes in steaming underway ( $X_2$ ) (see table 1),  $dX_1 = -dX_2$ .

Therefore, the elasticity of total fuel costs with respect to  $X_2$  evaluated at the means equals

$$\epsilon_{C, X_2} = \frac{C_2}{C} - \frac{C_1}{C} \frac{\bar{X}_2}{\bar{X}_1} \quad (2)$$

The share of fuel costs of not steaming,  $\frac{C_1}{C}$ , is small and the ratio of  $\bar{X}_2/\bar{X}_1$  is a fraction, e.g., for Frams it's 0.67. As a result, the elasticity of total fuel costs with respect to steaming underway is approximately equal to  $C_2/C$ .

Similarly it can be shown that the elasticity of fuel costs with respect to steaming not underway equals approximately  $C_3/C$ , its share of total fuel costs. Therefore, the sum of the two elasticities,  $X_2$  and  $X_3$ , should be less than but close to one; there are some fuel costs of not steaming.

In the next section we present estimates of marginal costs and elasticities for steaming underway and steaming not underway. We expect higher marginal costs for larger ships and for steaming underway compared with steaming not underway. We also expect the sum of the elasticities of steaming underway and steaming not underway to be just below one.

#### REGRESSION MODEL SPECIFICATION

Fuel consumption per ship-month (FC) is specified to be a quadratic function of steaming underway (UW) and steaming not underway (NW):

$$FC = a_0 + a_1 UW + a_2 UW^2 + a_3 NW + a_4 NW^2 + \text{error}.$$

Separate estimates are made for diesel, JP5, and "other" fuel for each of 13 destroyer-type ship classes. Definitions of variables and mean values are given in table 13.

Data on fuel consumption are missing for numerous ship-months. Estimates of steaming's effects for ship classes having few observations, e.g., FF 1036, FF 1037, may be less accurate than for others which are based on more ship-months, e.g., Frams, DDG 2, and CG 26. However, the weighted average effect is probably a relatively accurate estimate for destroyer-type ships overall.

TABLE 13

DEFINITION, MEAN VALUES AND STANDARD DEVIATIONS (+) OF VARIABLES IN FUEL CONSUMPTION REGRESSION MODEL, BY SHIP CLASS

Class (cases/ships)	Hours per month steaming <sup>a</sup> underway	Hours per month steaming not underway <sup>a</sup>	Monthly gallons of diesel	Monthly gallons of JP5	Monthly gallons of other fuel
Prans (960/33)	238 +187	173 +133	652 + 11,725	279 + 1,236	210,465 +180,985
DD 931 (170/7)	262 +194	179 +146	7,715 + 36,779	35,796 +106,504	252,116 +214,722
DDG 2 (378/14)	234 +181	200 +153	13,137 + 74,000	5,793 + 31,952	253,091 +203,406
DDG 31 (53/2)	304 +201	197 +139	31,090 + 63,335	8,714 + 37,444	324,036 +228,746
DDG 35 (26/2)	253 +194	205 +123	59 + 200	0	314,074 +217,045
DDG 40 (42/2)	208 +169	174 +146	71,988 +173,893	7,364 + 43,123	258,717 +231,859
FF 1036 (36/1)	288 +205	31 + 48	62,520 + 44,639	0	0
FF 1037 (35/1)	261 +201	86 + 91	0	99,287 +121,927	1,875 + 6,237
FF 1040 (186/7)	227 +179	101 +105	22,489 + 71,997	175,397 +164,015	0
FF 1052 (117/8)	214 +186	117 +115	1,539 + 11,736	7,756 + 26,641	130,631 +157,037
FG 1 (80/4)	210 +195	57 + 71	15,781 + 84,944	179,221 +174,168	0
CG 16 (99/4)	239 +180	213 +135	6,126 + 48,719	54,476 +151,504	320,831 +255,411
CG 26 (211/6)	271 +195	190 +142	2,196 + 21,217	10,183 + 56,443	350,616 +261,511

<sup>a</sup>Regression model included quadratic terms in steaming underway and steaming not underway.

## FINDINGS

Fuel consumption regression results are reported in table 14. For each ship class, one fuel accounts for at least 77 percent of consumption (see table 13). Reasonable results are obtained for the major fuel, especially for ship classes having relatively more observations.

For example, "other" fuel accounts for 99.6 percent of fuel consumption for Frams, which is our largest class (33 ships). Both UW and NW have positive and statistically significant effects on consumption of other fuel. The squared terms indicate these relationships are non-linear. For both UW and NW the squared terms are negative; it is statistically significant for UW using a two-tailed test. The  $R^2$  of .597 indicates a reasonably good fit, and the F statistic of 353.7 indicates that the regression is statistically significant at the .01 level. The regression results for the diesel and JP5 indicate that all variables are not statistically significant. Usage of these fuels may depend on steaming, but it is mostly determined by other factors.

Except for the FF 1052 class, UW has a positive and statistically significant effect on consumption for the major fuel. With respect to NW, the effect for the major fuel is positive in nine cases. It is statistically significant at the .05 level using a one-tailed test for only three ship classes -- Fram, DD 931, and CG 16. The results for squared terms vary among classes.

## THE MARGINAL COST OF STEAMING

The following equation is used to calculate the amount of fuel used on the margin:

$$\frac{\partial FC}{\partial UW} = a_1 + 2a_2 \overline{UW} ,$$

where  $a_1$  = regression estimate of the effect of UW  
 $a_2$  = regression estimate of the effect of  $UW^2$   
 $\overline{UW}$  = mean of steaming underway.

TABLE 14

## RESULTS OF REGRESSION ANALYSIS OF FUEL CONSUMPTION; BY SHIP CLASS AND FUEL

Class (cases/ships)	Fuel (percent) <sup>a</sup>	Constant	UW	UW <sup>2</sup>	NW	NW <sup>2</sup>	R <sup>2</sup>	F
FRAM (960/33)	Diesel (.1)	231.86244	5.91830 (.7722)	.01589 (1.2439)	1.50916 (.5957)	-.0128 (.7038)	.00495	1.1881
	JP5	336.57752	.83886 (1.0407)	-.00061 (.4549)	-1.50817 (1.5023)	.00125 (.6526)	.01092	2.63687 <sup>b</sup>
	Other (.3)	-24105.14224	912.84108 (12.1256) <sup>b</sup>	-.49031 (3.9089) <sup>b</sup>	452.08386 (4.8214) <sup>b</sup>	-.33107 (1.8539)	.59706	353.77136 <sup>b</sup>
	(99.6)							
DD 931 (170/7)	Diesel	-3588.97004	37.09532	-.03834	31.24514	.00107	.03181	1.35512
	(3.0)		(.6427)	(.4332)	(.4894)	(.0095)		
	JP5	-9724.58647	570.19606 <sup>b</sup>	-.76170 <sup>b</sup>	-270.00289	.47572	.08965	4.06203 <sup>b</sup>
	(12.0)		(3.5185) <sup>b</sup>	(3.0654) <sup>b</sup>	(1.5061)	(1.4749)		
DDG 2 (378/14)	Other	1498.98297	622.64883	.21520	541.60494 <sup>b</sup>	-.60761	.56025	52.55230 <sup>b</sup>
	(85.0)		(2.7420) <sup>b</sup>	(.6181)	(2.1560) <sup>b</sup>	(1.3444)		
	Diesel	-10658.55912	111.76195	-.14648	65.52424	-.04164	.02773	2.65954 <sup>b</sup>
	(5.0)		(1.4077)	(1.0596)	(.7389)	(.2707)		
DDG 31 (53/2)	JP5	720.20132	28.34885	-.02047	22.90995	-.06852	.01777	1.68735
	(2.0)		(.8228)	(.3412)	(.5953)	(1.0265)		
	Other	9977.59768	1263.90951 <sup>b</sup>	-1.00273 <sup>b</sup>	202.9145	-.08207	.50947	96.85119 <sup>b</sup>
	(93.0)		(8.1542) <sup>b</sup>	(3.7157) <sup>b</sup>	(1.1720)	(.2733)		
DDG 31 (53/2)	Diesel	-17232.46717	201.67497	-.20684	218.44396	-.49723	.09165	1.21070
	(8.0)		(1.3917)	(.9424)	(.8842)	(.9457)		
	JP5	971.23381	-60.00374	.09646	186.80950	.40773	.03550	.44174 <sup>b</sup>
	(2.0)		(.6797)	(.7214)	(1.2412)	(1.2728)		
DDG 31 (53/2)	Other	39457.94905	736.04653	.29312	-4.56911	.40350	.62457	19.96324 <sup>b</sup>
	(90.0)		(2.1875) <sup>b</sup>	(.5752)	(.0077)	(.3305)		

TABLE 14 (Cont'd)

Class (cases/ships)	Fuel (percent) <sup>a</sup>	Constant	UW	UW <sup>2</sup>	NW	NW <sup>2</sup>	R <sup>2</sup>	F
DDG 35 (26/2)	Diesel (.01)	70.67673	-1.27611 ( 1.4593)	.00156 (1.0056)	1.23182 ( 1.0206)	-.00173 ( .6924)	.18806	1.21600
	JP5	--	--	--	--	--	--	--
	Other (99.99)	-29183.19423	1537.69636 <sup>b</sup> ( 6.1852)	-.95459 <sup>b</sup> (2.1679)	333.82841 ( .9729)	-.32632 ( .4591)	.94409	88.65184 <sup>b</sup>
	Diesel (21.0)	-20086.99821	-401.60304 ( .7081)	1.44341 (1.4846)	688.6545 (1.1350)	-.92075 ( .9635)	.26237	3.29019 <sup>b</sup>
DDG 40 (42/2)	JP5	21791.81145	-366.64565 <sup>b</sup> ( 4.0755)	1.03293 (6.6981)	-89.31708 ( .9281)	.07353 ( .4851)	.69823	21.40283 <sup>b</sup>
	Other (77.0)	-6610.73999	2472.5335 ( 4.0538)	-3.33434 <sup>b</sup> (3.1891)	-133.98835 ( .2054)	.22814 ( .2220)	.52016	10.02726 <sup>b</sup>
	Diesel (100.0)	-13969.15474	504.51194 <sup>b</sup> ( 7.1154)	-.59255 <sup>b</sup> (5.6721)	252.3666 (1.1143)	-.91683 ( .8591)	.67434	16.04809 <sup>b</sup>
	JP5	--	--	--	--	--	--	--
FP 1036 (36/1)	Other ( 0.0)	--	--	--	--	--	--	--
	Other ( 0.0)	--	--	--	--	--	--	--
	Diesel ( 0.0)	--	--	--	--	--	--	--
	JP5	-11874.96531	746.72379 <sup>b</sup> ( 2.1296)	-.72189 (1.4154)	-272.09563 ( .3427)	1.11825 ( .4833)	.33734	3.81795 <sup>b</sup>
FP 1037 (35/1)	Other (98.0)	6012.59874	-49.08013 <sup>b</sup> ( 2.6236)	-.07868 <sup>b</sup> (2.8918)	4.00487 ( .0946)	-.00875 ( .0709)	.27918	2.90418 <sup>b</sup>
	Other ( 2.0)	--	--	--	--	--	--	--
	Diesel ( 0.0)	--	--	--	--	--	--	--
	JP5	--	--	--	--	--	--	--

TABLE 14 (Cont'd)

Class (cases/ships)	Fuel (Percent) <sup>a</sup>	Constant	UW	UW <sup>2</sup>	NW	NW <sup>2</sup>	R <sup>2</sup>	F
FP 1040 (186/7)	Diesel (11.0)	-8469.3667	56.70049 (.6213)	-.03875 (.2491)	183.32588 (1.2116)	.13268 (.3409)	.14217	7.49957 <sup>b</sup>
	JP5 (89.0)	15989.16137	748.1777 (5.4338) <sup>b</sup>	-.01857 (.0791)	-81.26172 (.3449)	-.01841 (.0313)	.62372	75.00627 <sup>b</sup>
	Other (0.0)	--	--	--	--	--	--	--
FP 1052 (117/8)	Diesel (1.0)	12.68413	-9.83252 (.4329)	.00833 (.2136)	49.47046 (1.6790) <sup>b</sup>	-.10538 (1.6094)	.02777	.7997
	JP5 (6.0)	3146.19642	-56.85142 (1.2448)	.21531 <sup>b</sup> (.7453)	.11204 (0)	-.01826 (.1387)	.23719	8.70627 <sup>b</sup>
	Other (93.0)	-8793.00952	172.68923 (.8236)	.58705 (1.6303)	407.80968 (1.4993)	.29053 (.4807)	.53722	32.5035 <sup>b</sup>
FFG 1 (80/4)	Diesel (8.0)	-17526.0902	191.6559 (1.1847)	-.30110 (1.1055)	396.04605 (1.1137)	-.59456 (.5939)	.06950	1.40050
	JP5 (92.0)	6763.71529	970.00147 (7.3428) <sup>b</sup>	-.26950 (1.2118)	-84.4424 (.2908)	-.56999 (.6972)	.84772	104.37959 <sup>b</sup>
	Other (0.0)	--	--	--	--	--	--	--
CG 16 (99/4)	Diesel (2.0)	-4823.61454	-38.05972 (.3561)	.14895 (.8156)	87.25678 (.6157)	-.18632 (.6792)	.04358	1.07071
	JP5 (14.0)	-12793.33338	470.11033 (1.4643)	-.48445 (.8833)	-242.78875 (.5704)	.78806 (.9566)	.10792	2.84292 <sup>b</sup>
	Other (84.0)	-37241.58775	1753.37538 <sup>b</sup> (4.5588) <sup>b</sup>	-1.62615 (2.4748) <sup>b</sup>	977.16466 (1.9162) <sup>b</sup>	-1.94111 (1.9667) <sup>b</sup>	.54946	28.65992 <sup>b</sup>

TABLE 14 (Cont'd)

Class (cases/ships)	Fuel (percent)	Constant	UW	UW <sup>2</sup>	NW	NW <sup>2</sup>	R <sup>2</sup>	F
CG 26 (211/6)	Diesel	1670.46225	4.28178	-.01528	-1.81096	.02512	.00963	.50080
	( 1.0)		( .1454)	( .3331)	( .0511)	( .3791)		
	JPS	-207.02079	88.53311	-.15375	48.58855	-.10126	.01432	.74845
	( 3.0)		( 1.1326)	(1.2625)	( .5168)	( .5759)		
	Other	-15759.75735	1261.78367	-.44933	364.01958	.09025	.64699	94.38988 <sup>b</sup>
	(96.0)		( 5.8218) <sup>b</sup>	(1.3307)	(1.3964)	( .1851)		

Source: Steaming and Fuel Data Master File.  
 aPercent of total gallons consumed.

<sup>b</sup>Statistically significant at .05 level. We use a one-tailed test for UW and NW and a two-tailed test for squared terms.

A similar method is used to estimate the effect of steaming not underway. Effects on gallons consumed are multiplied by fuel prices in October 1977 to obtain marginal fuel costs.<sup>1</sup>

Estimates of marginal cost per steaming hour for each fuel and ship class are given in table 15. Marginal costs for each fuel are added to yield the marginal costs of fuel consumption. Marginal costs of steaming underway generally increase as ship size increases. For example, they are generally lower for frigates than for DDs, and higher for DDGs and CGs than for the other ships. The marginal costs of steaming not underway are less than those of steaming underway, and they also tend to increase with ship size.

At the means of the data, the elasticity of steaming equals the ratio of marginal to average costs (also given in table 15). Elasticities of steaming underway and steaming not underway are given in table 16. As predicted, the elasticities sum to about one for most ship classes.

The elasticities for destroyer-type ships, estimated by weighting the estimate for each ship class by the number of ships in the class, are .7774 for steaming underway and .2006 for steaming not underway. Since the relative sizes of these shares is about as expected and they sum to just under one, the regression analysis seems to have yielded reasonably good estimates for destroyer-type ships overall.<sup>2</sup> Because of small samples, however, results for some individual ship classes are probably far less accurate.

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<sup>1</sup> During the period of analysis "other" fuel was mostly Navy standard. The price of Navy standard in October 1977 is used to estimate the price of other fuel. In the early 1970s ships were being converted to use Navy distillate. As a result our estimates on costs may be slightly too low for two reasons. First, the price of Navy standard (41.4) was lower than the price of Navy distillate (44.1) in October 1977. Second, fuel consumption seems to have increased by about seven percent because of conversion (see "Logistic Reference Data," pp. 1-5). The combined effects may increase fuel costs by about ten percent relative to estimates from the regression analysis.

<sup>2</sup> Regression estimates of elasticities slightly understate steaming's share of fuel costs. Using equation (2) to adjust for the bias yields estimates of .79 for the share of steaming underway, .20 for the share of steaming not underway, and .01 for the share of not steaming.

TABLE 15

AVERAGE AND MARGINAL COSTS OF FUEL CONSUMPTION PER  
HOUR, BY SHIP CLASS, FUEL AND TYPE OF STEAMING

Ship class	Fuel <sup>a</sup>	Type of steaming			
		Underway		Not underway	
		Average costs	Marginal costs	Average costs	Marginal costs
FRAM I	Other	365.98	281.52	503.42	139.93
	Diesel	1.22	N/A	1.68	N/A
	JP5	0.52	0.24	0.71	-0.51
	Total	367.72	281.76	505.81	139.42
DD 931	Other	398.27	305.53	582.91	133.72
	Diesel	12.93	N/A	19.18	N/A
	JP5	60.42	75.85	88.20	-43.22
	Total	471.62	381.38	690.29	90.50
DDG 2	Other	447.95	329.54	523.71	70.79
	Diesel	24.97	18.73	29.44	21.85
	JP5	11.02	N/A	12.79	N/A
	Total	483.94	348.27	565.94	92.64
DDG 31	Other	441.32	377.57	681.03	63.34
	Diesel	45.49	N/A	70.47	N/A
	JP5	12.79	N/A	19.40	N/A
	Total	499.60	377.57	770.90	63.34
DDG 35	Other	513.77	437.60	634.25	81.97
	Diesel	0.10	N/A	0.13	N/A
	JP5	0	N/A	0	N/A
	Total	513.87	437.60	634.38	81.97
DDG 40	Other	515.02	450.02	615.62	-22.36
	Diesel	154.32	87.86	184.64	164.13
	JP5	15.44	27.34	18.52	-28.66
	Total	684.78	565.22	818.78	113.11
FF 1036	Other	0	N/A	0	N/A
	Diesel	96.78	73.59	899.58	86.97
	JP5	0	N/A	0	N/A
	Total	96.78	73.59	899.58	86.97
FF 1037	Other	2.90	-2.9	9.11	.828
	Diesel	0	N/A	0	N/A
	JP5	167.58	163.61	508.91	-34.84
	Total	170.48	160.71	518.02	-34.01

TABLE 15 (Cont'd)

Ship class	Fuel <sup>a</sup>	Type of steaming			
		Underway		Not underway	
		Average costs	Marginal costs	Average costs	Marginal costs
FF 1040	Other	0	N/A	0	N/A
	Diesel	44.15	16.95	99.46	93.21
	JP5	340.89	325.90	766.02	-37.48
	Total	385.04	342.85	865.48	55.73
FF 1052	Other	252.54	175.95	462.02	197.06
	Diesel	3.21	N/A	5.80	N/A
	JP5	15.88	16.32	29.11	-2.20
	Total	271.63	192.27	496.93	194.86
FFG 1	Other	0	N/A	0	N/A
	Diesel	33.45	N/A	123.54	N/A
	JP5	376.17	377.94	1386.50	-65.71
	Total	409.62	377.94	1510.04	-65.71
CG 16	Other	558.07	404.48	623.48	62.51
	Diesel	11.60	N/A	12.93	N/A
	JP5	100.99	106.28	112.90	41.01
	Total	670.66	510.76	749.31	103.52
CG 26	Other	535.72	421.45	763.83	164.77
	Diesel	3.57	N/A	5.35	N/A
	JP5	16.76	N/A	23.81	N/A
	Total	556.05	421.45	792.99	164.77

Source: Navy Petroleum Office.

<sup>a</sup>Other @ \$.414/gallon (price Navy standard); diesel @ \$.446/gallon; and JP5 @ \$.441/gallon. Costs are in dollars.

<sup>b</sup>Relationships having F values less than about 2.0 are not significant at the .10 level. For these, coefficients are typically not significant and the particular fuel accounted for a very small percent of the total fuel consumption. These fuels are excluded from calculations of marginal fuel costs.

TABLE 16  
ESTIMATES OF FUEL CONSUMPTION SHARES FOR STEAMING UNDERWAY AND  
STEAMING NOT UNDERWAY

	<u>Steaming</u>	<u>Not underway</u>	<u>Sum</u>	<u>Ships in cohort</u>
FRAM I	.766	.276	1.042	33
DD 931	.807	.131	.938	7
DDG 2	.720	.164	.884	14
DDG 31	.754	.082	.836	2
DDG 35	.851	.129	.980	2
DDG 40	.825	.138	.963	2
FF 1036	.760	.097	.857	1
FF 1037	.943	-.066	.877	1
FF 1040	.891	.064	.955	7
FF 1052	.708	.392	1.100	8
PFG 1	.924	-.044	.880	4
CG 16	.761	.138	.899	4
CG 26	.757	.208	.965	<u>6</u>
Total				91
Weighted average	.7774	.2006	.978	

## THE TRADEOFF BETWEEN CASREPT DOWNTIME AND FUEL COSTS

Following from the definition of an elasticity, the effect of a 25 percent reduction in steaming on CASREPT downtime is calculated as follows:

$$\begin{aligned} \text{Downtime} = & (.25) \times (\text{average CASREPT downtime}) \\ & \times (\text{elasticity of CASREPT downtime with respect to steaming}). \end{aligned} \quad (3)$$

Steaming's effect on fuel costs is similarly calculated:

$$\begin{aligned} \text{Fuel costs} = & (.25) \times (\text{average fuel costs}) \\ & \times (\text{elasticity of fuel costs with respect to steaming}). \end{aligned} \quad (4)$$

Data required to evaluate equations (3) and (4) are given in table 17. We estimate weighted average fuel costs for destroyer-type ships to be \$101,351 per month given October 1977 fuel prices. (The other data in table 17 were given earlier in tables 10, 11, and 16 but we repeat them again here for convenience.)

The effects of a 25 percent reduction in steaming on CASREPT downtime and fuel costs are given in table 18. Per ship per month a 25 percent reduction in steaming would increase CASREPT downtime by 532 hours for C2 and 95 hours for C3/C4 CASREPTs, but it would lower fuel costs by about \$20,000. Thus there is a tradeoff between CASREPT downtime and fuel costs due to steaming. An increase of 27 hours of C2 and 4.8 hours of C3/C4 CASREPT downtime are incurred to save \$1,000 of fuel costs.

Historically, declines in hours steaming underway have caused one-for-one increases in hours not steaming. We assume this relationship holds when estimating the cost-effectiveness of steaming. The sensitivity of results to this assumption is analyzed below.

Table 19 gives estimates of the net effects of a 25 percent increase in steaming underway, i.e., 62 hours per month, by source of time, not steaming and steaming not underway. Entries for not steaming were given earlier in table 18. To calculate the entries for steaming not underway we subtract the partial effects of reducing steaming not underway by 62 hours, from the partial effects of increasing steaming underway by 62 hours. The partial effects of steaming not underway are

TABLE 17

DATA USED TO EVALUATE EQUATIONS 3 AND 4

CASREPT	CASREPT downtime elasticity with respect to steaming underway	Fuel cost elasticity with respect to steaming underway	CASREPT downtime per ship month	Fuel costs per ship month (\$ thousands)
C2	-0.589	0.7774	3,618	101.351
C3/C4	-0.386	0.7774	918	101.351

TABLE 18

EFFECTS OF A 25 PERCENT REDUCTION IN STEAMING ON  
CASREPT DOWNTIME AND FUEL COSTS

CASREPT	Downtime hours	Fuel savings (\$ thousands)	Downtime per \$1000 fuel saving
C2	532	19.2	27.0
C3/C4	95	19.2	4.8

calculated in the same way we calculated the effects of steaming underway in table 18.

TABLE 19

EFFECTS OF A 25 PERCENT INCREASE IN STEAMING UNDERWAY ON CASREPT DOWNTIME AND FUEL COSTS, BY SOURCE OF TIME

<u>Source</u>	<u>CASREPT</u>	<u>Reduction downtime</u>	<u>Increase fuel costs (\$000)</u>	<u>Reduction downtime per \$1000 increase in fuel costs</u>
Not steaming	C2	532	19.2	27.7
	C3/C4	95		4.9
Steaming not underway <sup>a</sup>	C2	356	10.65	33.4
	C3/C4	76		7.1

<sup>a</sup>Estimated by deducting the effects of declines in steaming not underway from the effects of steaming underway.

If the source of steaming time is hours not steaming, our assumption throughout, CASREPT downtime declines by 532 hours for C2 and 95 hours for C3/C4 CASREPTs. If it is hours steaming not underway, CASREPT downtime falls by only 356 hours for C2 and 76 hours for C3/C4 CASREPTs, but fuel savings also fall from \$19,750 to only \$10,650.

The last column in table 19 gives the reduction in downtime per \$1000 increase in fuel costs - the return to steaming per thousand dollars invested. The return is fairly insensitive to the source of time: as we go from not steaming to steaming not underway, the return increases from 27.7 to 33.4 for C<sub>2</sub> and 4.9 to 7.1 for C<sub>3</sub>/C<sub>4</sub> CASREPTs. Thus the Navy can expect to reap roughly the same benefits of increased steaming regardless of the source of time used to increase it.

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